



# Top Pair production with W/Z/photon

Andrey Loginov  
Yale University



Snowmass Energy Frontier Workshop  
April 3-6 2013, BNL

# LHC and Tevatron

- Tevatron = **Top discovery** machine
  - 1.96 TeV proton-antiproton machine
  - In some of the results presented Tevatron still holds the first place
- LHC = **Top factory**
  - **7, 8 and beyond (design energy 14) TeV**
  - In 7 and 8 TeV operation delivered  $\sim$ 2 orders of magnitude more top quarks than at the Tevatron
    - Sensitive to some of the top couplings already, and need more energy / data to get more
- Reference document for the presentation
  - [http://www.snowmass2013.org/tiki-download\\_file.php?fileId=40](http://www.snowmass2013.org/tiki-download_file.php?fileId=40)

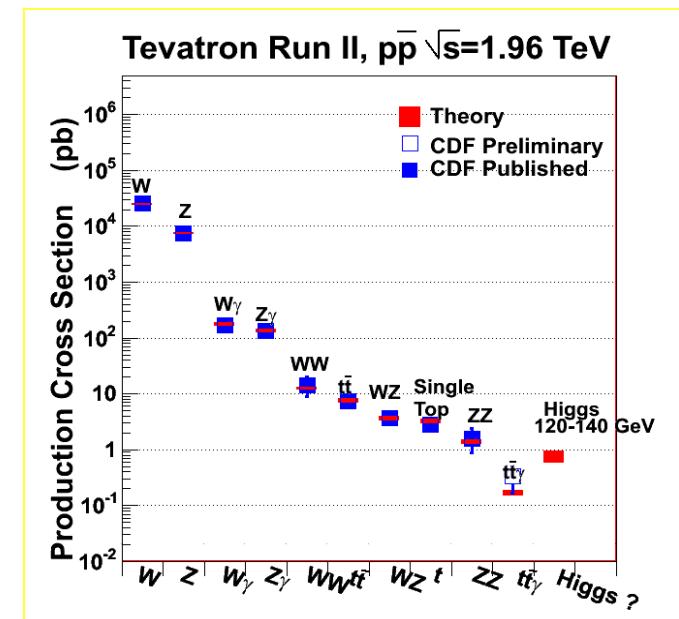
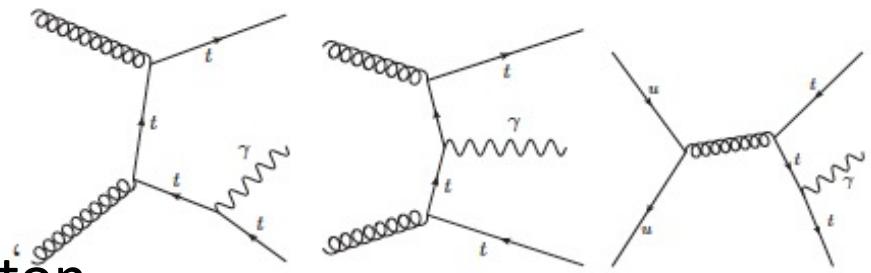


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# ttbar + Photon

- Sensitive to top charge and to top-photon couplings
  - Need to identify photons coming from top
    - Suppress photons from W, leptons, jets (gg fusion ttbar production dominates @LHC => less ISR QED)
- Control sample / Background to ttbar + Higgs, Higgs to diphoton
- For now can only measure the cross section
  - **CDF**: first evidence of ttbar + photon production (using **6 fb<sup>-1</sup>** of data)
    - Dominated by stat. uncertainty
  - **ATLAS**: preliminary measurement with **1 fb<sup>-1</sup>** (but still below 3 sigma significance)
    - Dominated by systematics: photon ID, ISR/FSR, jet energy scale



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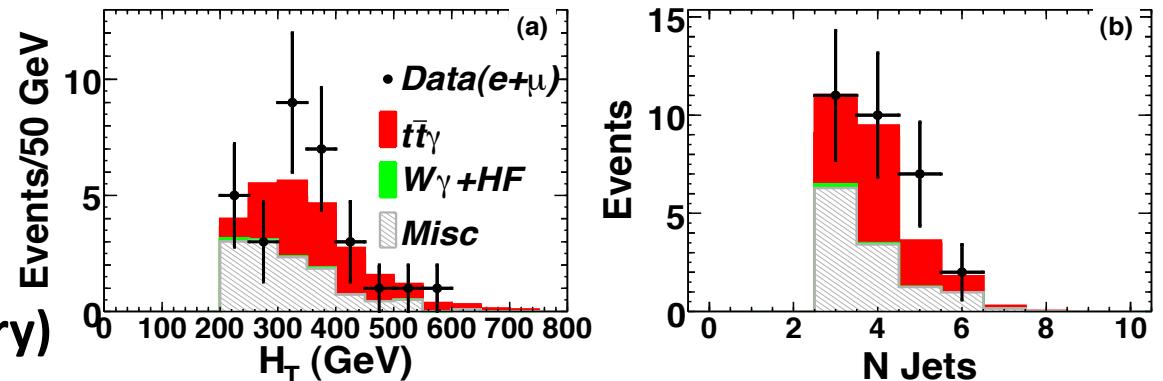


# ttbar + Photon: Results

CDF, Phys.Rev.D84:031104,2011

$$\sigma_{t\bar{t}\gamma} = 0.18 \pm 0.08 \text{ pb}$$

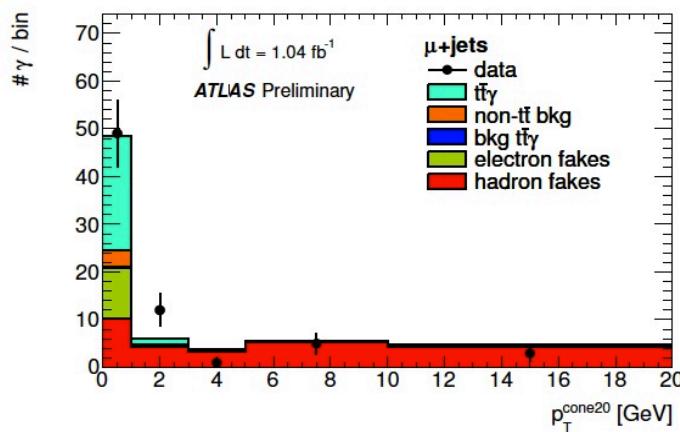
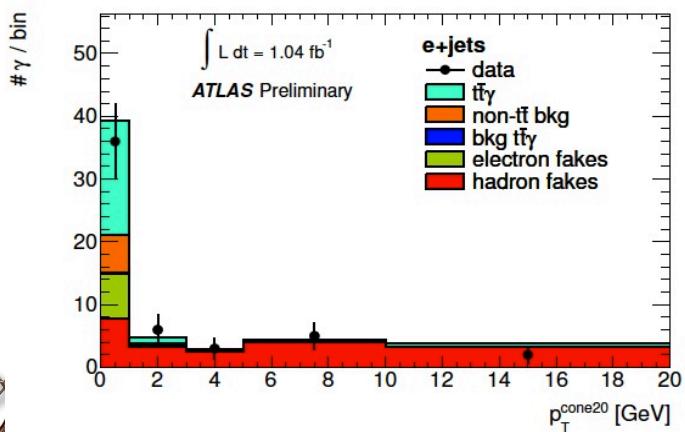
$$\sigma_{t\bar{t}\gamma}^{total} = 0.17 \pm 0.03 \text{ pb (Theory)}$$



ATLAS, ATLAS-CONF-2011-153

$$\sigma_{t\bar{t}\gamma} = 2.0 \pm 0.5 \text{ (stat.)} \pm 0.7 \text{ (syst.)} \pm 0.08 \text{ (lumi.) pb}$$

$$2.1 \pm 0.4 \text{ pb (Theory)}$$



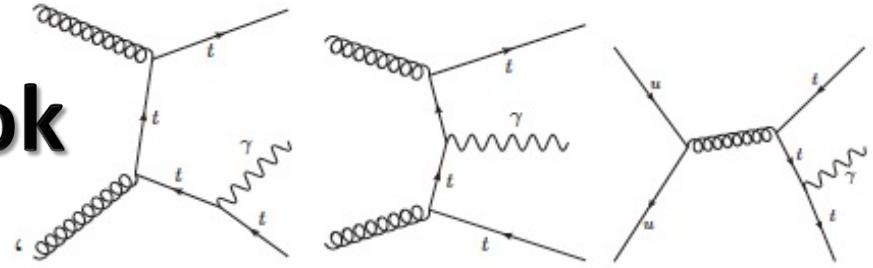
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# ttbar + Photon: Outlook



- With current 2011 / 2012 data
  - Should be able to measure ttbar + photon cross section with 5+ sigma significance (separately in 7 TeV and in 8 TeV data)
  - Can play around with  $\Delta R$  (photon, X) cuts to isolate photons coming from top, [Phys.Rev. D71 \(2005\) 054013](#)
- 7  $\rightarrow$  14 TeV: LO cross section increases by a factor of 5 ([MadGraph](#), photon  $p_T > 20$  GeV)
  - **300 fb<sup>-1</sup>**: few thousands events expected => can go for couplings measurement, [Phys.Rev. D71 \(2005\) 054013](#)
    - In both lepton + jets and dilepton channels
  - **3000 fb<sup>-1</sup>**: differential measurements (couplings as a function of photon  $p_T$  etc)

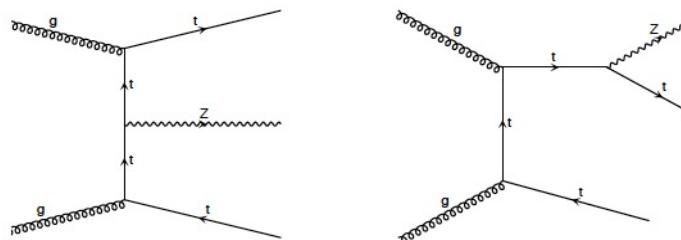


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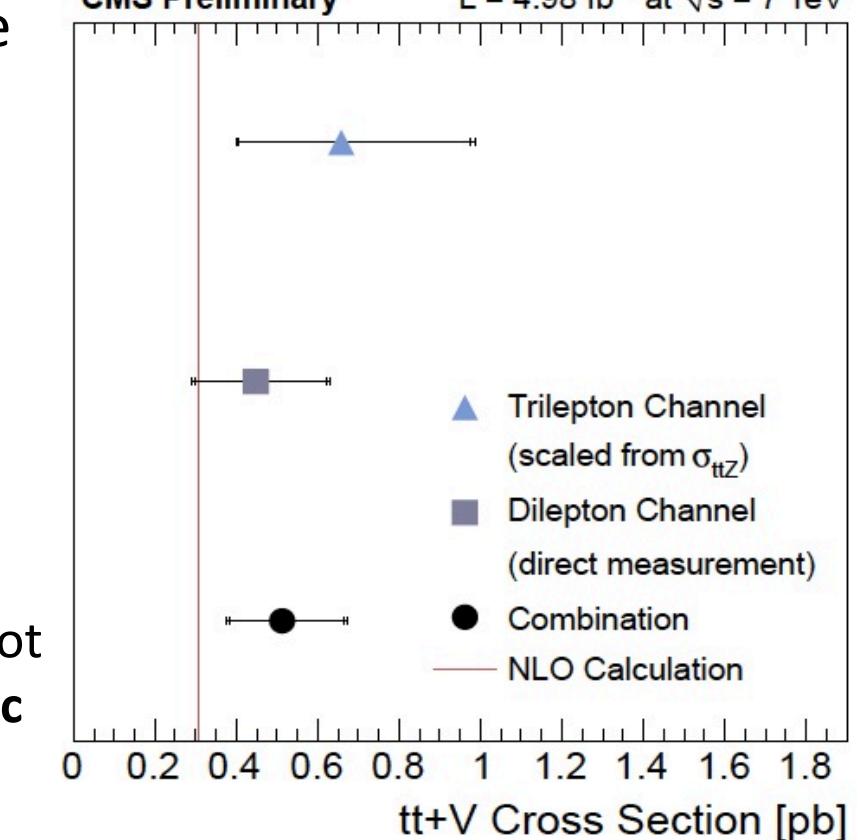
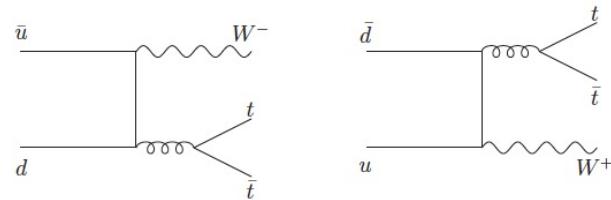
# ttbar + V



[CMS-PAS-TOP-12-014](#)

- ttbar + Z production is directly sensitive to ttZ couplings
- For now can only measure the cross section
  - CMS: first evidence of ttbar + Z production as well as ttbar + V cross section measurement
    - Dominated by stat. uncertainty
  - ATLAS: generic ttbar + Z selection, hence not sensitive. Set a limit for the production xsec  
**< 0.71 pb**

[ATLAS-CONF-2012-126](#)



$$\sigma_{t\bar{t}Z} = 0.30^{+0.14}_{-0.11}(stat)^{+0.04}_{-0.02}(syst) \text{ pb}$$

$$\sigma_{t\bar{t}V} = 0.51^{+0.15}_{-0.13}(stat)^{+0.05}_{-0.04}(syst) \text{ pb}$$



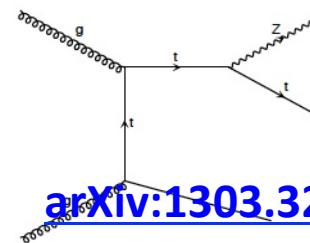
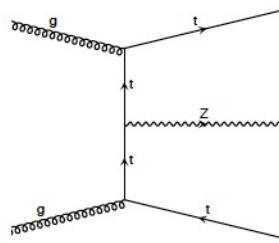
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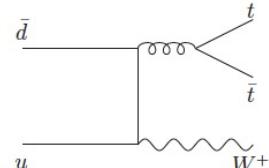
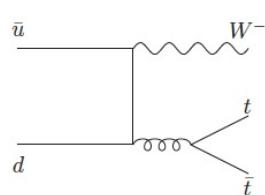
# ttbar + V



[arXiv:1303.3239 \(submitted to the PRL\)](https://arxiv.org/abs/1303.3239)

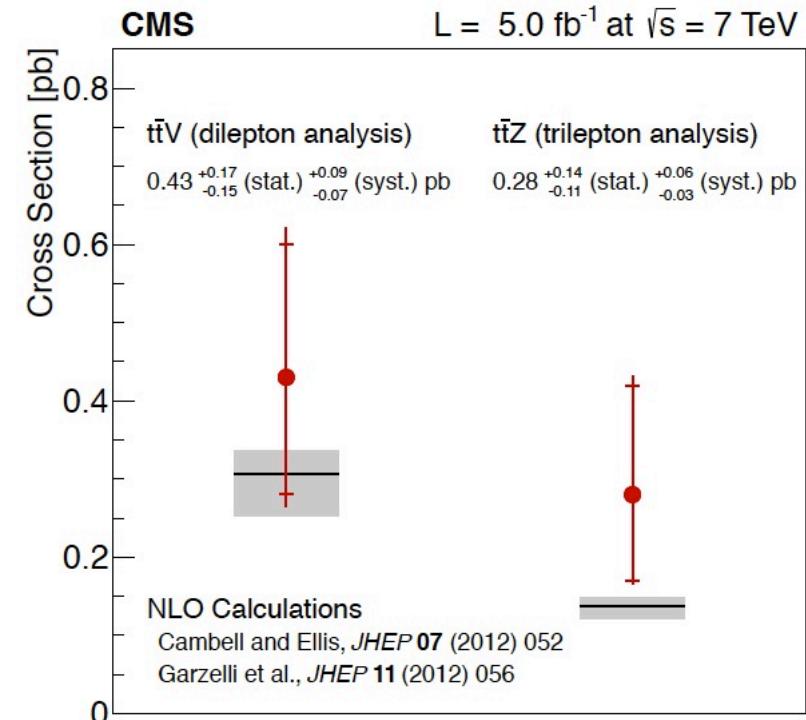
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- For now can only measure the cross section
  - CMS: first evidence of ttbar + Z production as well as ttbar + V cross section measurement
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**< 0.71 pb**

[ATLAS-CONF-2012-126](#)



$$\sigma_{t\bar{t}Z} = 0.28^{+0.14}_{-0.11} \text{ (stat.)} \quad {}^{+0.06}_{-0.03} \text{ (syst.) pb}$$

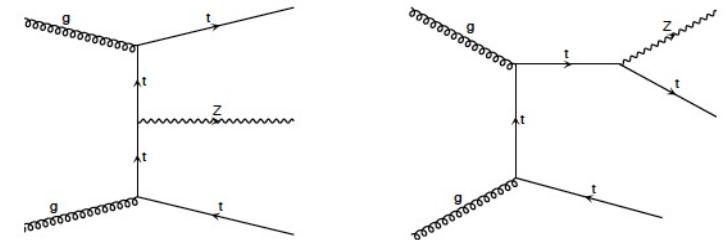
$$\sigma_{t\bar{t}V} = 0.43^{+0.17}_{-0.15} \text{ (stat.)} \quad {}^{+0.09}_{-0.07} \text{ (syst.) pb}$$



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# ttbar + Z: Outlook



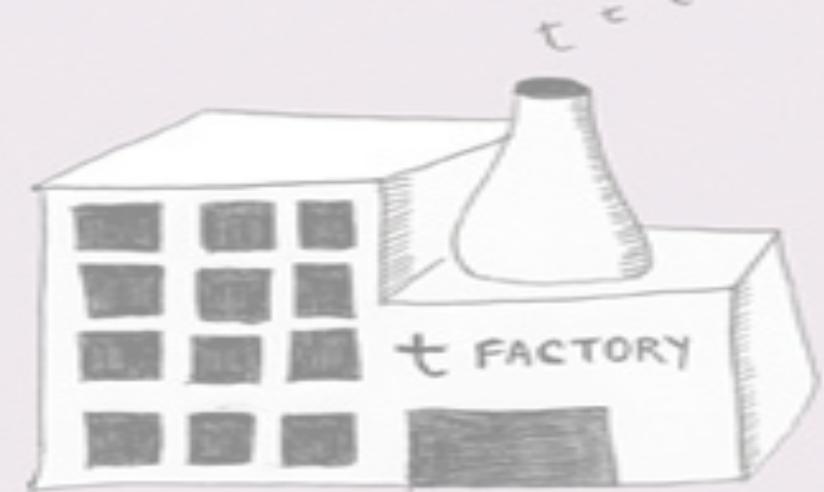
- With current 2011 / 2012 data
  - 7 → 8 TeV: ttZ LO cross section increases by a factor of 1.4 (**MadGraph; see also talk of N.Kidonakis this morning**)
    - Stat. uncertainty will decrease by a factor of 2.5
    - Still **limited by statistics**
    - ttW has a similar increase in the xsec
- 7 → 14 TeV: LO cross section increases by a factor of 10 (**MadGraph**)
  - **300 fb<sup>-1</sup>**: ttZ axial (vector) couplings can be determined with an uncertainty **45-85% (15-20%)**, **Phys.Rev. D71 (2005) 054013**
  - **3000 fb<sup>-1</sup>**: a factor of **3** better



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# Summary / Outlook



- LHC keeps providing top quarks in unprecedented quantities
- Precision measurements, detailed studies, improving of understanding of the heaviest known particle and its properties
- We will learn a lot in the years to come...
  - ...if we better plan it, we will learn even more ;)



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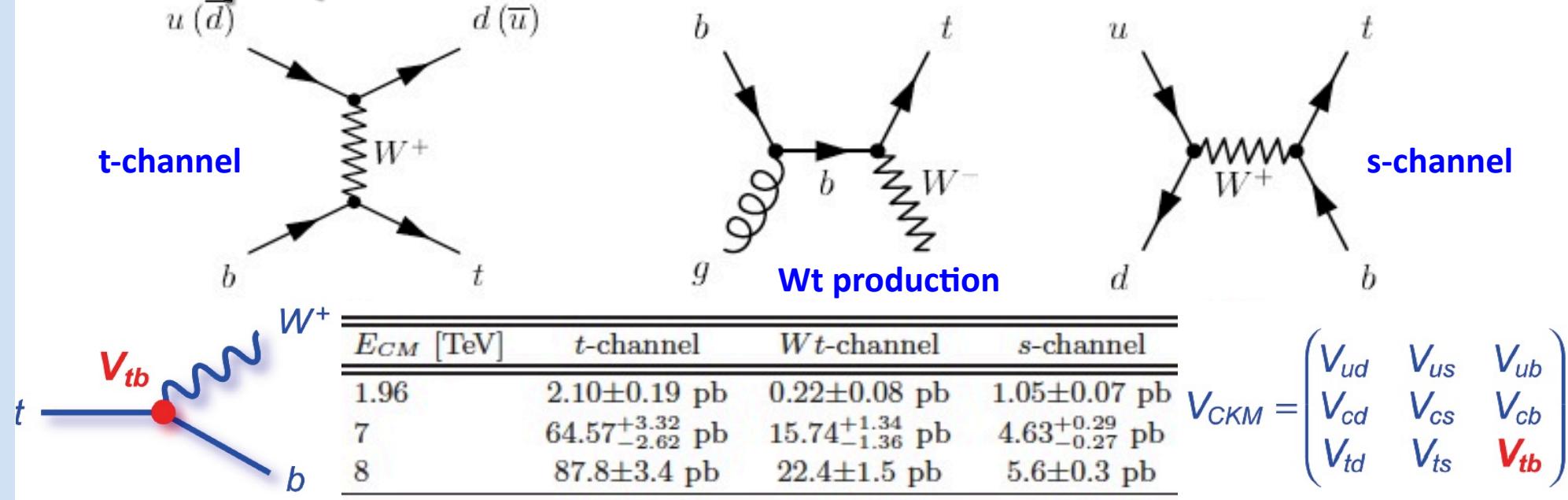


# Top pair production at ATLAS

# BACKUP



# Top Quark Weak Interaction Measurements



- The top-quark can be produced singly by an electroweak **Wtb**-vertex
- Motivation
  - Complementary information on top-quark properties
  - Direct measurement of the CKM matrix element  $\mathbf{V_{tb}}$
  - Sensitive to many models of new physics
  - Information on the **b-quark PDF**



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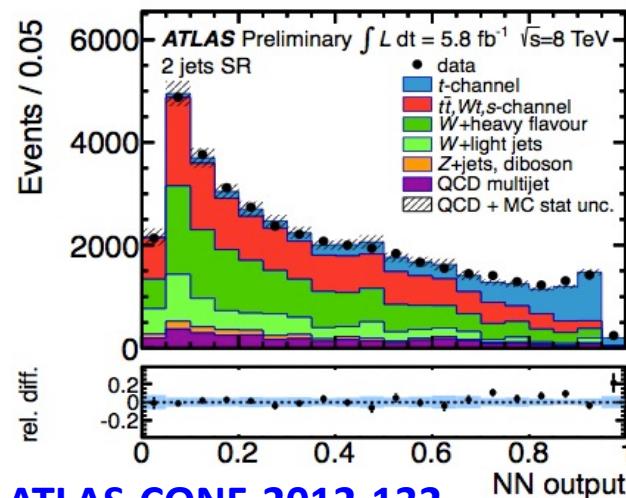
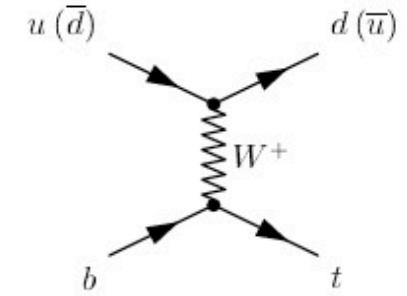
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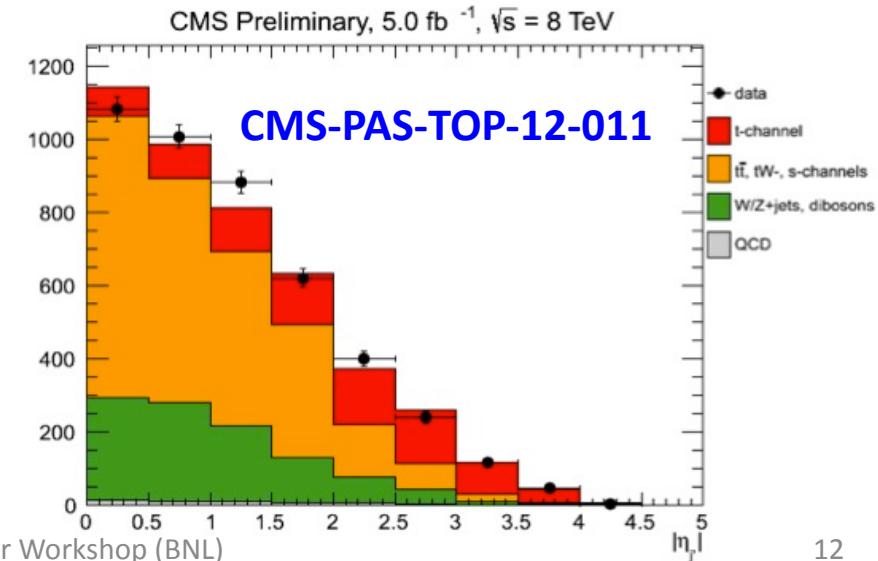
# Single top: t-channel

- Method
  - ATLAS:** binned maximum likelihood fit to the NN output distribution
  - CMS:** eta distribution of the recoil jet
- Measurement
  - ATLAS:**  $95 \pm 18 \text{ pb}$ ,  $V_{tb} = 1.04 +0.10/-0.11$
  - CMS:**  $80.1 \pm 5.7(\text{stat}) \pm 11.0(\text{syst}) \pm 4.0(\text{lumi}) \text{ pb}$ ,  $V_{tb} > 0.81 @ 95\% \text{ CL}$
- Dominant Systematics
  - ATLAS:** Jet Energy Scale (JES), b-tagging, and ISR/FSR
  - CMS:** statistical, JES, t-chan generator



ATLAS-CONF-2012-132

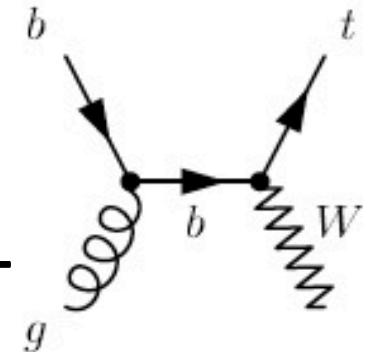
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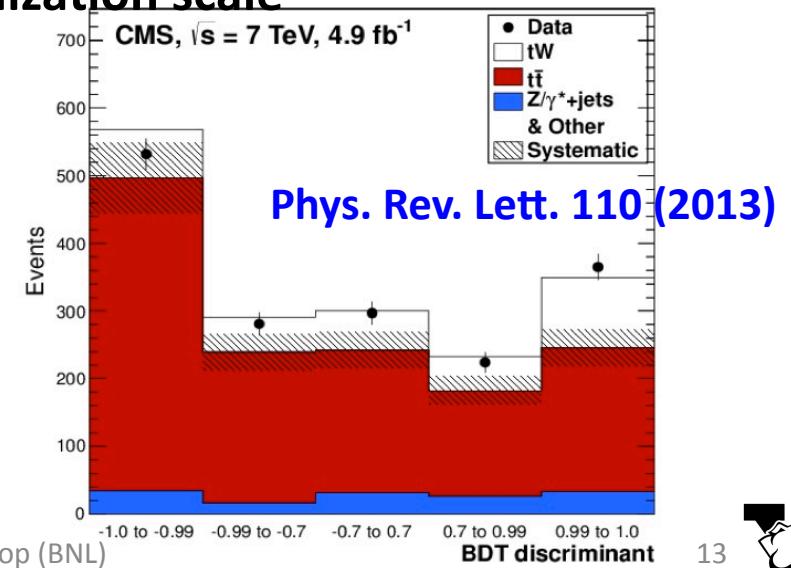
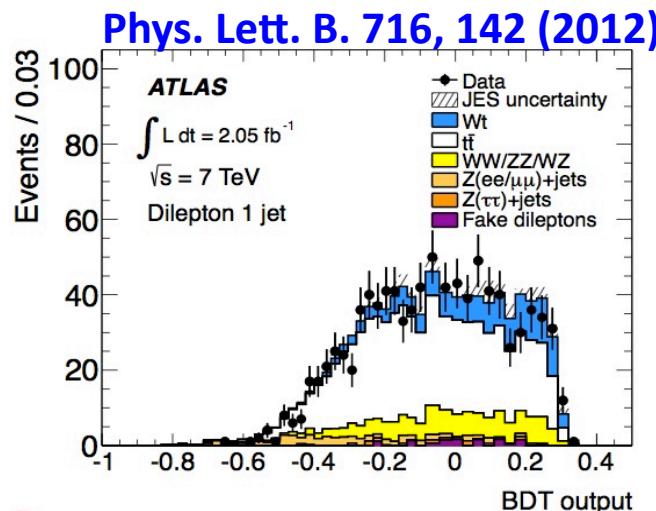
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# Single top: Wt-channel



- Negligible @ Tevatron, 2nd highest single top xsec @ LHC
- Evidence for Wt @ 7 TeV (both used Template fit to a BDT output)
  - ATLAS: 3.3 sigma,  $16.8 \pm 2.9(\text{stat}) \pm 4.9(\text{syst}) \text{ pb}$
  - CMS: 4.0 sigma,  $16.4^{+5/-4} \text{ pb}$
- Dominant Systematics
  - ATLAS: Jet Energy Scale (JES), statistics, and ISR/FSR
  - CMS: JES, statistics, factorization/renormalization scale



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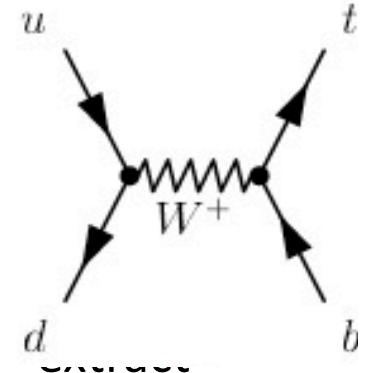
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# Single top: s-channel

- Negligible @ LHC, 2nd highest single top xsec @ Tevatron
- Measurements from CDF and Dzero
  - Measure xsec for t-channel and s-channel together, then the components
  - **CDF:  $1.81 +0.63/-0.58$  pb, CDF Note 10793**  
[http://www-cdf.fnal.gov/physics/new/top/confNotes/cdf10793\\_SingleTop\\_7.5\\_public.pdf](http://www-cdf.fnal.gov/physics/new/top/confNotes/cdf10793_SingleTop_7.5_public.pdf)
  - **DZERO:  $0.68 +0.38/-0.35$  pb, Phys.Rev. D84 (2011) 112001**
- Dominant Systematics
  - **CDF:** background normalization
  - **DZero:** JES, JER, corrections to b-tagging efficiencies, and the correction for jet-flavor composition in W+jets events



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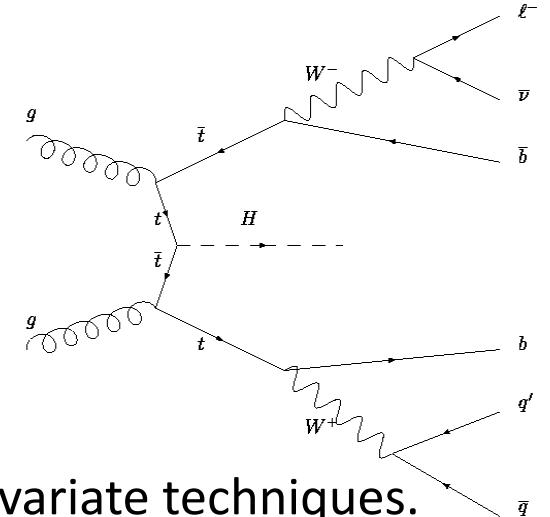
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# ttbar + Higgs

- ttbar + Higgs => square of top Yukawa coupling
  - One of the key points of Higgs physics program
- Tevatron (CDF)
  - Searches in lepton + jets and all-hadronic channel. Multivariate techniques.
  - Lepton+jets: Observed (expected) limit = **20.5 (12.6) x SM**  
**Phys.Rev.Lett. 109 (2012) 181802**
  - 0-lepton: Observed (expected) limit = **36.2 (26.2) x SM**  
**CDF note 10582**  
[http://www-cdf.fnal.gov/physics/new/hdg/Results\\_files/results/tthNoLepton\\_110708/](http://www-cdf.fnal.gov/physics/new/hdg/Results_files/results/tthNoLepton_110708/)
- LHC
  - CMS: analyzed both **dilepton** and **lepton + jets** channels:  
observed (expected) limit **4.6 (3.8) x SM**, **CMS-PAS-HIG-12-025**
  - ATLAS: analyzed **lepton + jets** channel:  
observed (expected) limit = **13.1 (10.5) x SM**, **ATLAS-CONF-2012-135**



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# ttbar + Higgs: Outlook

- Will profit from increased energy, statistics, as well as better understanding of backgrounds: ttbar + bbbar, ttbar + (di)photon

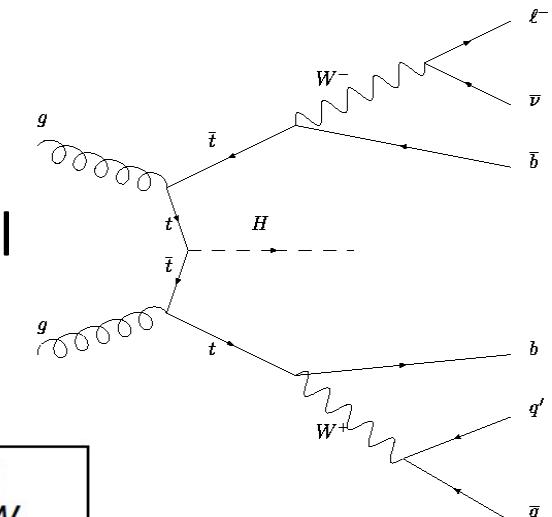
$$\begin{aligned} gg &\rightarrow H \\ qq &\rightarrow q\bar{q}H \\ gg &\rightarrow t\bar{t}H \\ qq' &\rightarrow VH \end{aligned}$$

$\longleftrightarrow$

$$g_{HXX} = g_{HXX}^{\text{SM}} (1 + \Delta_X)$$

$\longleftrightarrow$

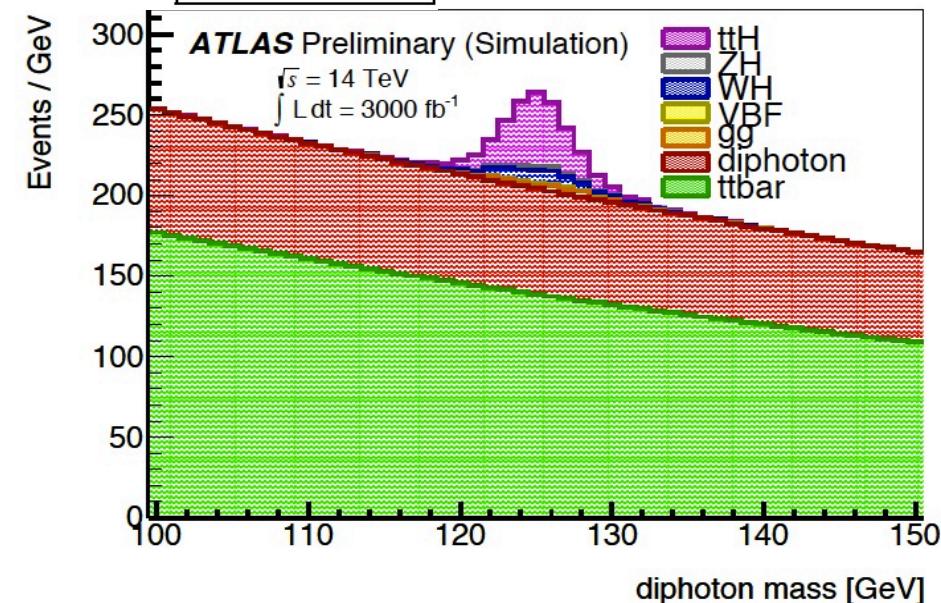
$$\begin{aligned} H &\rightarrow ZZ \\ H &\rightarrow WW \\ H &\rightarrow b\bar{b} \\ H &\rightarrow \tau^+\tau^- \\ H &\rightarrow \gamma\gamma \end{aligned}$$



- ATLAS:
- Higgs partial widths ratio ( $\Gamma_t/\Gamma_g$ ) measurement precision to better than 55% (25%) with 300 (3000)  $\text{fb}^{-1}$ ,

**ATL-PHYS-PUB-2012-004**

- ttbar+Higgs, Higgs  $\rightarrow$  diphoton/dimuon
- ttbar selection is looser than for the mainstream ttbar



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# Jet Multiplicity in Top Pair Events

- Motivation
  - **Constrain** ISR/FSR models at the scale of the top quark mass
  - **Test** perturbative QCD in the LHC energy regime
- Lepton + Jets channel (ATLAS), Dilepton channel (CMS)
  - Jet multiplicities as a function of jet  $p_T$  thresholds:
    - ATLAS: 25, 40, 60 and 80 GeV, [ATLAS-CONF-2012-155](#)
    - CMS: 30 and 60 GeV, [CMS-PAS-TOP-12-023](#)
  - Subtract backgrounds and **unfold to particle level**
    - Account for detector efficiencies, resolution effects and biases
  - **Dominated by systematics in all regions**
  - **Compare** to various Monte Carlo simulation models
    - ALPGEN+HERWIG
    - ALPGEN+PYTHIA ( $\alpha_s$ -down and  $\alpha_s$ -up variations)
    - MC@NLO+HERWIG
    - POWHEG+PYTHIA
    - MadGraph + PYTHIA



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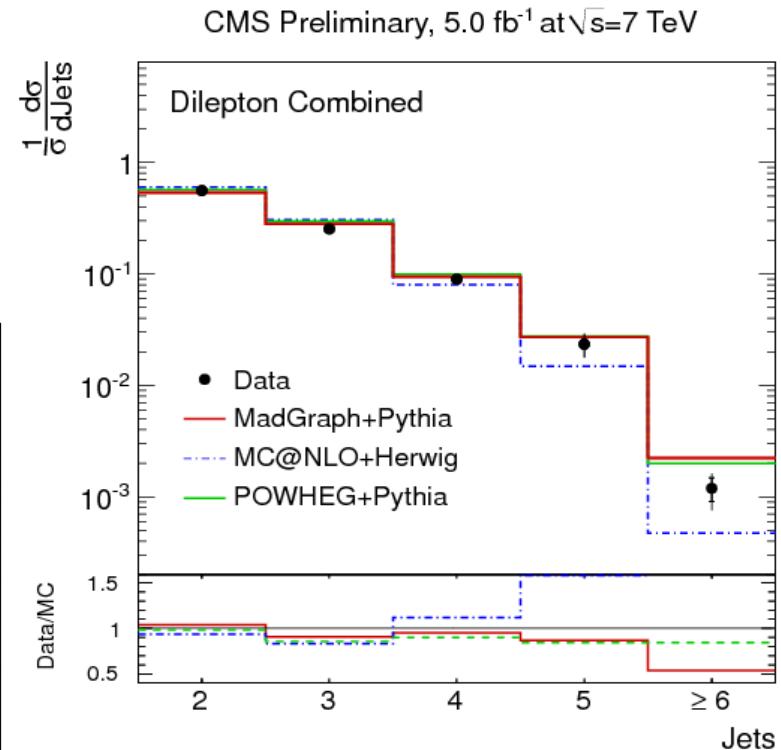
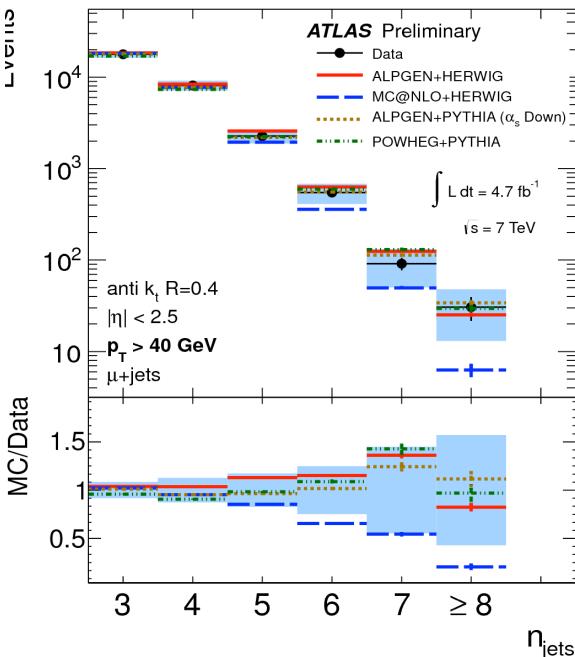
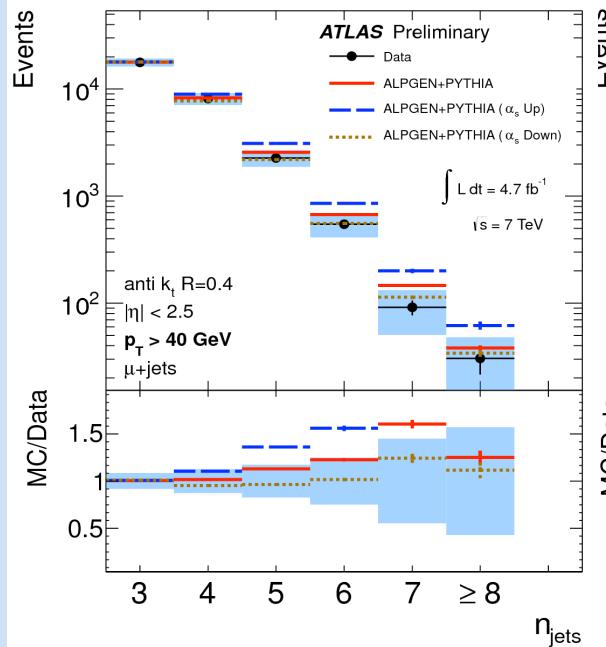


# Jet Multiplicity in Top Pair Events: Unfolded

ATLAS-CONF-2012-155

## ATLAS Disfavored:

- MC@NLO + Herwig
- ALGGEN+Pythia with  $\alpha_s$ -up variation



CMS-PAS-TOP-12-023

## CMS Disfavored:

- MC@NLO + Herwig



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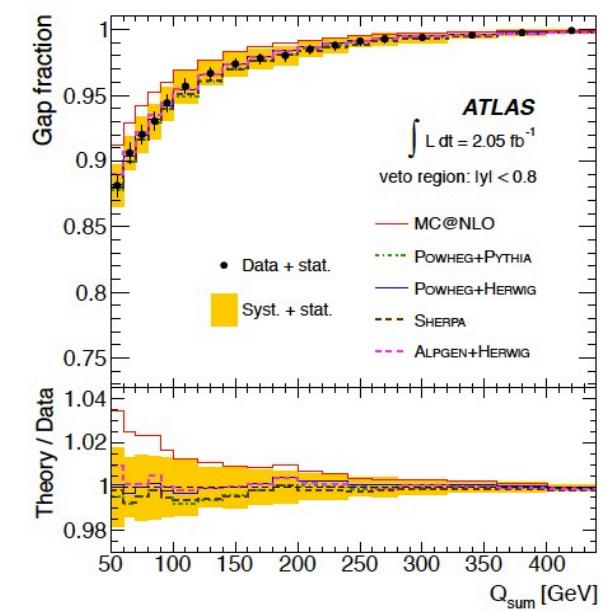
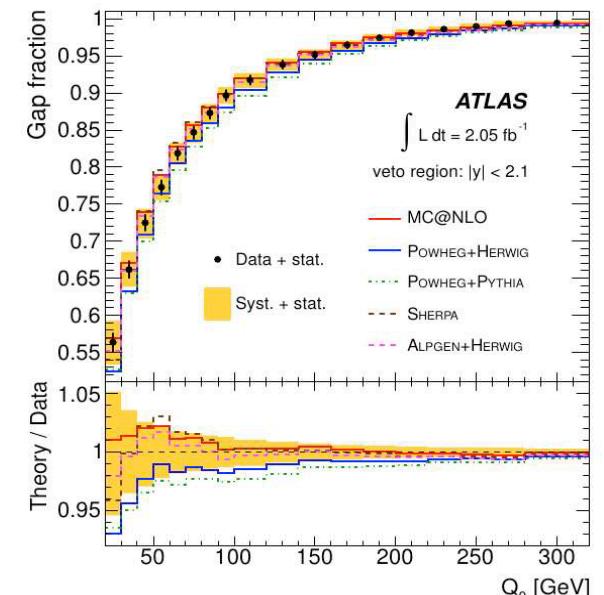
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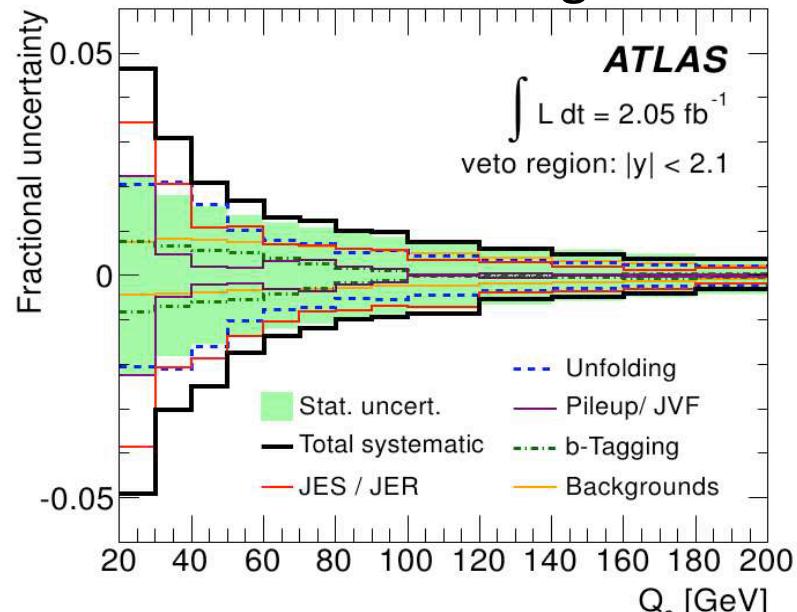
# ttbar with Jet Veto: ATLAS

- **Gap fraction**  $f(x) = n(x)/N$ 
  - $N$  is the **total number** of selected ttbar events
  - $n(x)$  is the  **$N$  (ttbar events with additional jet veto)**
    - $x = Q_0$ : no additional jets with  $p_T > Q_0$  in a rapidity interval (CMS calls the variable  $p_T$ )
    - $x = Q_{\text{sum}}$ : the scalar sum of the additional jets'  $p_T$  in the rapidity interval  $< Q_{\text{sum}}$  (CMS calls the variable  $H_T$ )
- Sensitive to
  - ISR / FSR
  - Effects of different shower models
  - Higher order effects of different generators
- Conclusions (ATLAS, **lepton + jets** channel)
  - **MC@NLO underestimates** the data in the central region  $|y| < 0.8$
  - All models describe data in the full  $|y| < 2.1$  veto interval, but **tend to predict too much jet activity**



# ttbar with Jet Veto: CMS

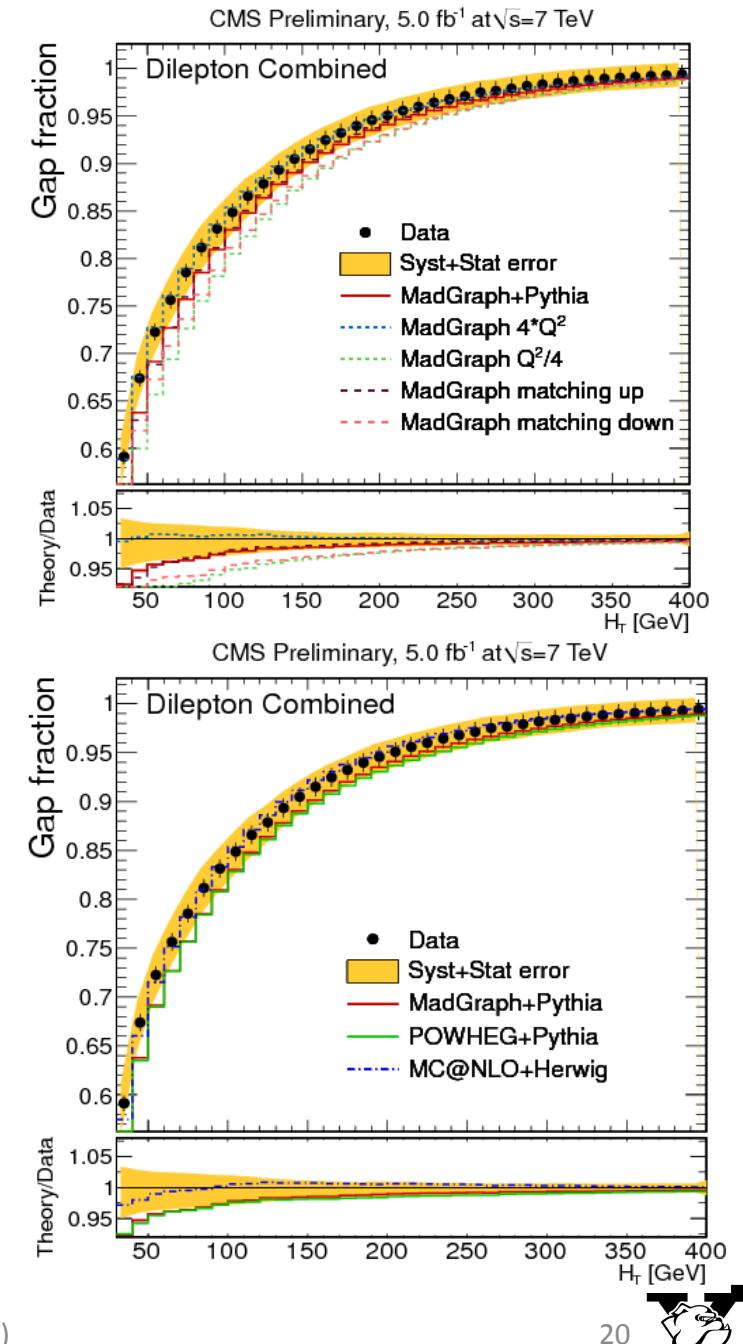
- Conclusions (CMS, dilepton channel)
  - MC@NLO gives the **best prediction**
  - **Increasing  $Q^2$  scale in MadGraph** improves the data/MC agreement
- Overall comment
  - Already **dominated by systematics** both for ATLAS and CMS
  - With more data can go into more details



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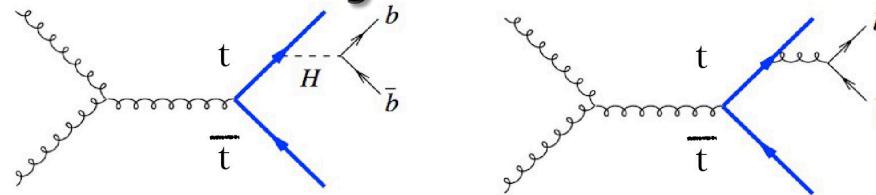
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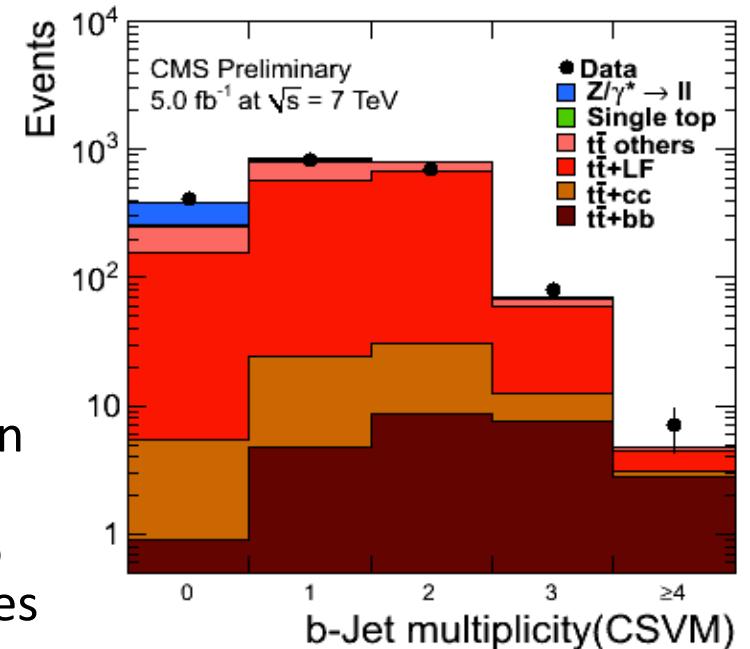
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# ttbar+jets HF Composition: CMS



- Motivation:**
  - ttbar+Higgs is important channel for measurement of top quark to Higgs boson coupling
  - Irreducible background from ttbar in association with bbbar as predicted by higher order QCD
  - Measure cross section ratio for uncertainties to cancel, e.g. luminosity, jet and lepton efficiencies
- Method:**
  - Fit to the b-tagged jet multiplicity distribution
- Dominant Systematic Uncertainties:**
  - b-tag scale factor (**18%**), Q2 scale (**6%**), MC (**3%**)



$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 3.6 \pm 1.1(\text{stat.}) \pm 0.9(\text{sys.})\%$$



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# Top quark + jets: Outlook

- More statistics / more energy
  - Detailed understanding of top pair production with jets
    - Reduce systematics – report ratios of multiplicites
    - Finer binning (as stat.uncertainty is not an issue)
  - Feedback to theory community
  - Better precision SM predictions for beyond-the-SM searches
- For rare processes ( $t\bar{t}$ bar + Heavy Flavor)
  - More statistics will help
  - Can measure  $c\bar{c}$ bar and  $b\bar{b}$ bar separately
  - Expect input from theory community
    - NLO calculation is challenging...



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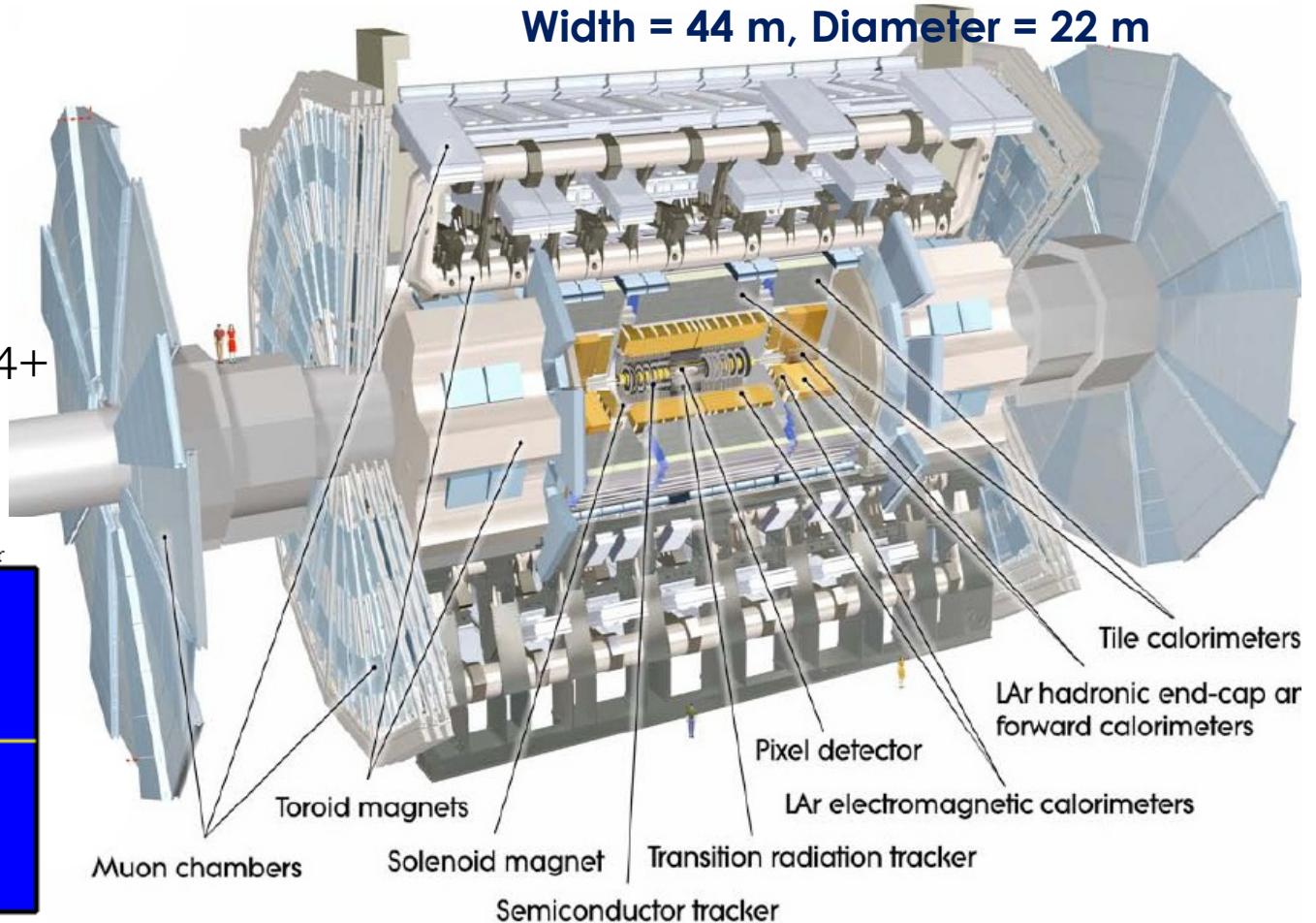
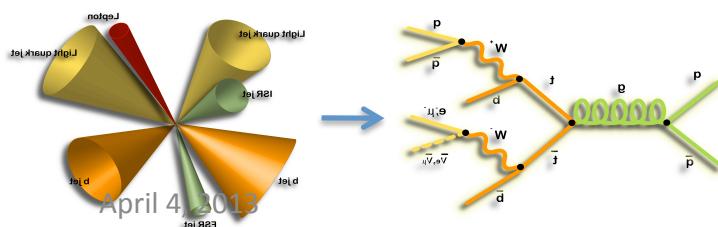
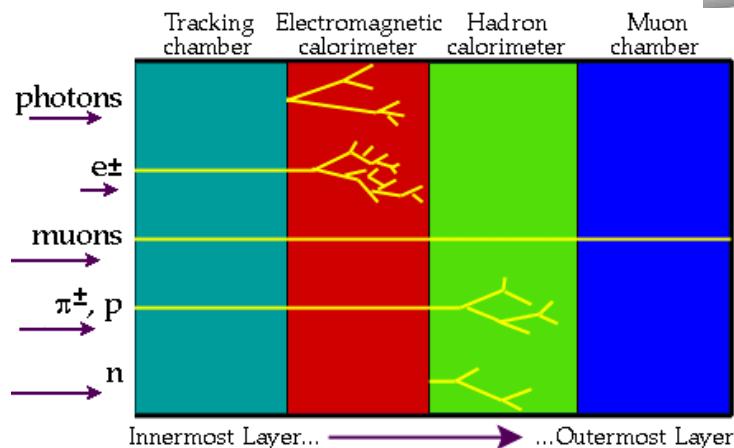
# LHC / ATLAS

Width = 44 m, Diameter = 22 m

## Large Hadron Collider

- p-p collider
- Center of mass energy
  - $\sqrt{s} = 7 \text{ TeV}$  @ 2010-11
  - $\sqrt{s} = 8 \text{ TeV}$  @ 2012
  - $\sqrt{s} = 13-14 \text{ TeV}$  @ 2014+
- Multi-purpose experiments:

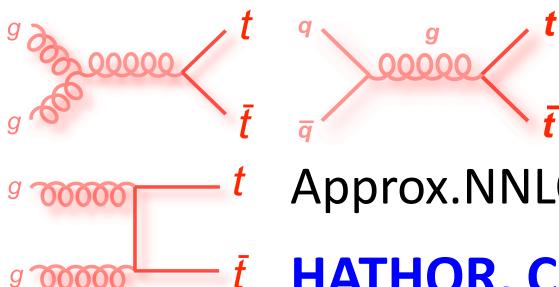
### ATLAS and CMS



## Subdetectors and identified objects:

- Trackers: electrons, muons, jets, taus, photons
- Calorimeters: electrons, muons, jets, taus, photons
- Muon Detectors: muons

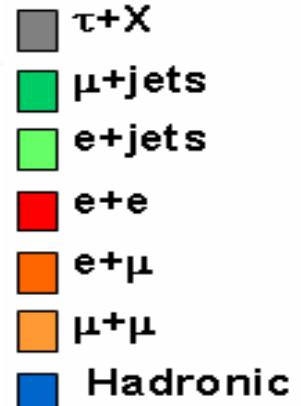
# Introduction



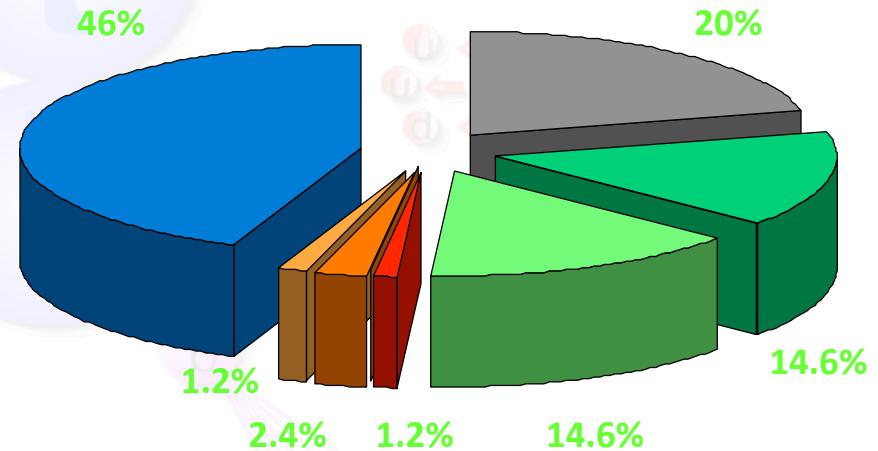
$$\sigma_{t\bar{t}} = 165^{+11}_{-16} \text{ pb}$$

Approx.NNLO,  $m_{top} = 172.5 \text{ GeV}$ , 7 TeV pp collisions

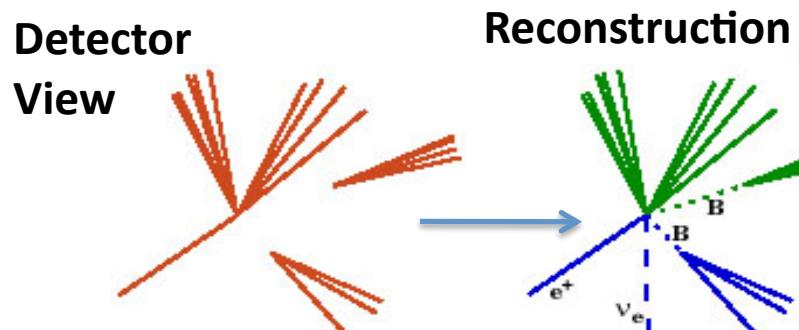
**HATHOR, Comput. Phys. Commun., 182 (2011) 1034**



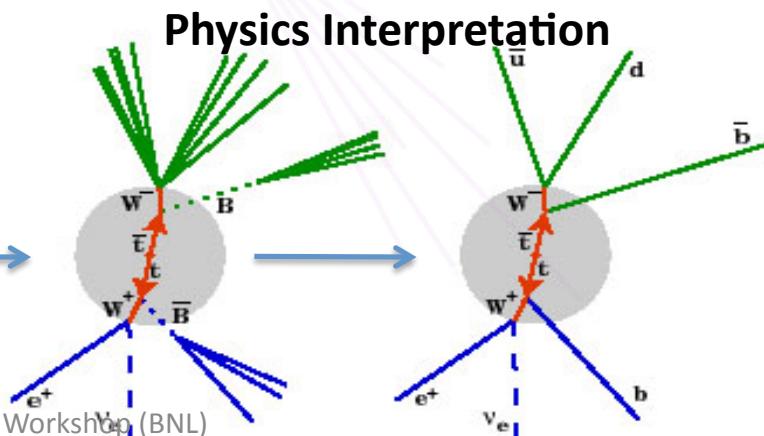
- Top pair production at the LHC through  $gg$  (80%) and  $q\bar{q}$  (20%)
- Top pair decay modes
  - The more jets, the more challenging the systematics get (Jet energy scale, ISR/FSR etc)



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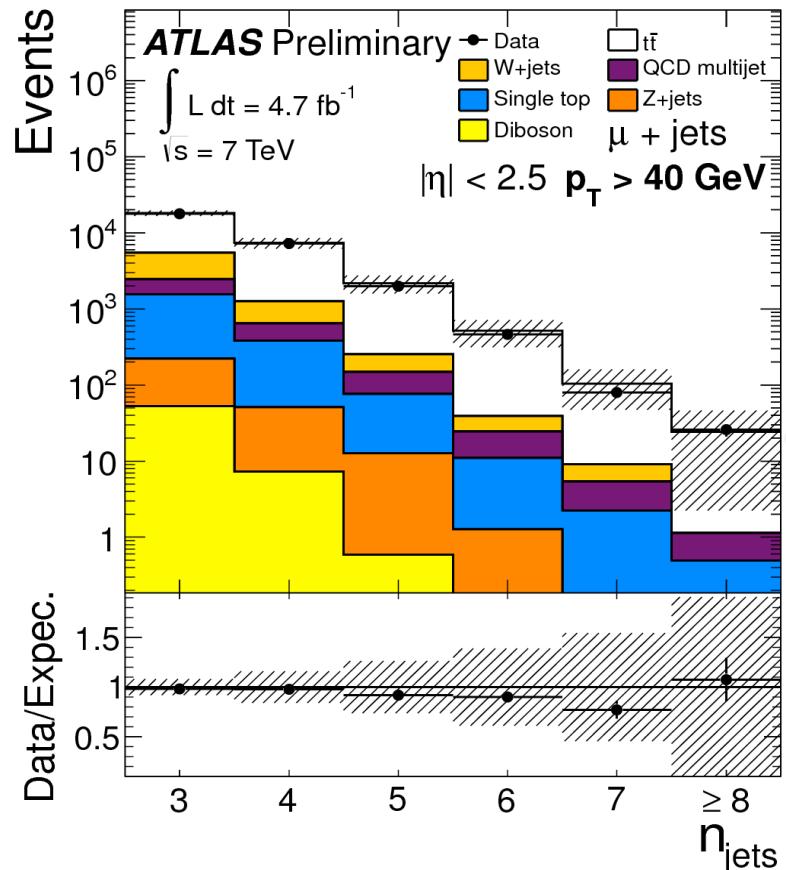




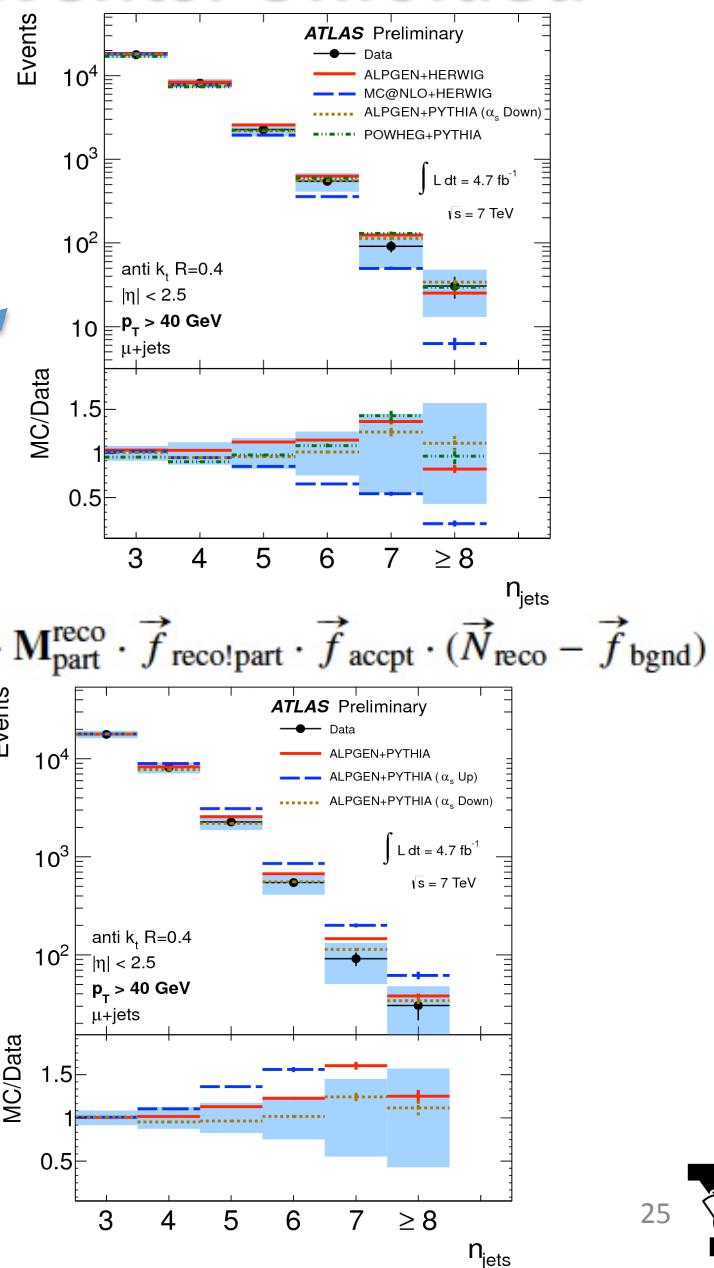
# Jet Multiplicity in Top Pair Events: Unfolded

**Disfavored:**

- MC@NLO + Herwig
- ALPGEN+Pythia with  $\alpha_s$ -up variation



$$\vec{N}_{\text{part}} = \vec{f}_{\text{part!reco}} \cdot M_{\text{part}}^{\text{reco}} \cdot \vec{f}_{\text{reco!part}} \cdot \vec{f}_{\text{accept}} \cdot (\vec{N}_{\text{reco}} - \vec{f}_{\text{bgnd}})$$



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